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TITLE APPLICATIONS OF COMPLEX TERRAIN METEOROLOGICAL MODELS TO EMERGENCY RESPONSE MANAGEMENT

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Abstract

The Office of Health and Environmental Research (OHER), U.S. Department of Energy (DOE), has supported the development of mesoscale transport and diffusion and meteorological models for several decades. The model development activities are closely tied to the OHER field measurement program which has generated a large amount of meteorological and tracer gas data that have been used extensively to test and improve both meteorological and dispersion models. This paper briefly discusses the history of the model development activities associated with the OHER atmospheric science program. The discussion will then focus on how results from this program have made their way into the emergency response community in the past, and what activities are presently being pursued to improve real time emergency response capabilities. Finally, fruitful areas of research for improving real time emergency response modeling capabilities are suggested.

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Introduction

For the past two decades, going back to the time when the present U.S. Department of Energy's (DOE) Office of Health and Environmental Research (OHER) was part of the Atomic Energy Commission, DOE has supported the development of atmospheric transport models for the purpose of investigating the dispersion of radioactive material. This work encompassed various scales of motion from local to regional to hemispheric. For a period of time in the 1970s, DOE-sponsored research was also focused on the dispersion of pollutants from conventional power plants, and more recently, some modeling efforts with DOE sponsored research have concentrated on problems associated with acid deposition (Patrinos and Knox, 1989).

Over this 20 year period, a significant amount of DOE-sponsored modeling research has made its way into the emergency response arena. For example, it was through this research support that the first Atmospheric Release Advisory Capability, the ARAC (Dickerson *et al.*, 1983; 1985) prototype, located at the Lawrence Livermore National Laboratory, was developed. This prototype was subsequently used as a basis for the present ARAC system which now serves as a U.S. DOE, Department of Defense, and Naval Reactor emergency response resource, and also supports other federal and state agencies. The core modeling capability within this system, the MATHEW/ADPIC models (Dickerson *et al.*, 1983), was largely developed through DOE/OHER funding. Most recently, assessments of the Chernobyl nuclear reactor accident illustrate the capability that has emerged from the work sponsored by DOE (Lange *et al.*, 1988).

Recently, through the OHER-sponsored Atmospheric Studies in Complex Terrain (ASCOT) program, the development of prognostic meteorological models has emerged as a major focus, along with the continual evaluation of the diagnostic and other [illegible] models. The suite of models encompassed in the ASCOT program includes hydrostatic second-moment turbulence closure models, a non-hydrostatic finite element model, a non-hydrostatic [illegible] model, a Lagrangian statistical diffusion model, a Lagrangian-Eulerian hybrid diffusion model, and a puff trajectory model. The model development activities are closely tied to the ASCOT field measurement program, which has generated a large amount of meteorological and tracer data (Gudiksen *et al.*, 1989) that have been used extensively to test and improve both meteorological and dispersion models.

In the following section we review the models, either totally or partially sponsored by the DOE OHER, that have moved, or for which there are plans to move, from the research phase into the emergency response operational phase. It is not possible in this paper to discuss all the model development activities sponsored by OHER over the past 20-plus years; therefore most of the work discussed in this paper is rather recent although some has been in progress over a period of years through continued research efforts. Readers are referred to Addis *et al.* (1989) for evaluation of model performances.

In the last section of this paper we discuss research areas where we believe there is a potentially high pay off for improving emergency response capabilities as they pertain to a better understanding and utilization of our knowledge of atmospheric boundary layer physics. We also comment on how we are using the recent advancements in microcomputer technology to improve the emergency response modeling capability.

MODELS

Puff model

Rao *et al.* (1989) modified an integrated puff model by Petersen and Lavdas (1986). This model, developed at Atmospheric Turbulence and Diffusion Division/NOAA, is capable of using a time dependent two-dimensional wind field supplied by the user and puff dispersion parameters based on on-site turbulence data to estimate concentrations at up to 100 receptors over level terrain. The modifications by Rao *et al.* account for gross elevation differences between the tracer release site and the receptor sites in complex terrain, restricted lateral dispersion of puffs due to the presence of valley sidewalls, well mixed lateral and/or vertical dispersion regimes in a deep narrow valley, subsidence in the valley drainage flow for elevated releases, and output concentrations in user specified units. The reader is referred to that paper for details.

Rao *et al.* (1989) performed simulations of the 1984 ASCOT data (Clements *et al.*, 1989) for one elevated release and one surface release, with each release occurring on a different night. Although remotely sensed wind data were available, they used only data from tethered balloon sites shown in Fig. 1, as they felt these are more representative of the kind and quality of data likely to be available at a typical site survey. The balloon soundings at 90 min intervals were interpolated spatially and temporally to obtain hourly averaged wind distributions for the entire valley. The puff dispersion parameters were based on the standard deviations of horizontal and vertical wind direction fluctuations, σ_a and σ_β, derived by Rao and Schaub (1989) from the turbulence measurements in Brush Creek. Hourly concentrations from 0000–1000 hrs (MST) for the elevated release (September 26, 180 m height, referred to as Test 2) and the surface release (September 30, 5 m height, Test 4) cases were computed at 51 ground-level samplers on the three arcs and along the valley axis.

For the elevated release case, the mean of the concentrations observed at all 51 receptors, O, is 40 pl/l (picolitres/litre) while the mean of the predicted concentrations, P, is 21 pl/l. The corresponding results for the surface release case are 85 pl/l and 73 pl/l, respectively. These results suggest that the latter simulations are generally better, though the correlation coefficients (0.21 and 0.23) are nearly the same for the two tests. The observed data show large spatial and temporal variability. The ratio of the standard deviation to the mean of the observed concentrations is large — about 1.4 for both cases. The values of this ratio for the predictions is about 1.0 for Test 2 and 0.8 for Test 4. At many of the receptors, the predicted and observed hourly averaged concentrations agree to within factors of two to six. Figures 2a and 2b show the hourly concentrations, averaged over all 51 sampling stations, for Test 2 and Test 4, respectively. The corresponding plots for the samplers in arc 1 only are shown in Figs. 3a and 3b. For both tests, the results for the entire simulation period are better at arc 1, which had the most (25) samples and was the farthest (7.2 km) from the source.

These satisfactory results suggest that the modified puff model approach may offer a simple and inexpensive means to simulate the transport and dispersion of pollutants in valley environments. Future plans include additional tracer data simulations, and development of a puff model which could accept three-dimensional wind fields to better represent the effects of shear, subsidence, and differential heating of valley sidewalls on the transport and distribution of the puffs.

Puff models are appealing because of their ability to address light wind conditions and short-term releases. In addition, some important effects of complex terrain can be represented through spatially variable wind field data, and adjustments for gross elevation differences, as discussed above. Deposition and gravitational settling of gaseous or particulate pollutants, and the parameterized effects of fast exothermic chemical reactions can also be incorporated in the puff model.

as shown by Hicks *et al.* (1989). It is not surprising, therefore, that a puff-trajectory approach is often used to satisfy the need for both a simple "Class A" model for site evaluation and real-time emergency response application, and a more complicated "Class B" model suitable for safety and risk assessment, emergency preparedness, and post-accident assessment applications (see e.g., Hicks *et al.*, 1989; Eckman and Dobosy, 1989; Ramsdell *et al.*, 1983).

HOTMAC/RaPTAD

The basic equations of Los Alamos National Laboratory's HOTMAC (Higher Order Turbulence Model for Atmospheric Circulations) for mean wind, temperature, mixing ratio of water vapor, and turbulence are given in Yamada and Bunker (1988, 1989).

Surface boundary conditions are constructed from the empirical formulas by Dyer and Hicks (1970) for the nondimensional wind and temperature profiles. Strictly speaking, the formulas are valid only for horizontally homogeneous surfaces. It is assumed, however, that the same relations are fair approximations over nonhomogeneous terrain, provided that the formulas are applied sufficiently close to the surface. It should be noted that vegetation plays an active part in the apportionment of available heat energy between convective (sensible and latent) and conductive (into the soil) components. The technique discussed here is intended to address only the case of bare soil where the surface is conventionally characterized by roughness lengths. The complexity introduced by biological factors and drag forces due to tall trees (canopy flow) are beyond the scope of the present study. Use of the similarity formulae requires knowledge of the surface temperatures; a method to obtain the surface temperature is discussed below.

The temperatures in the soil layer are obtained by solving the heat conduction equation. Appropriate boundary conditions are the heat energy balance at the soil surface, and specification of the soil temperature or soil heat flux at a certain depth.

The lateral boundary values are obtained by integrating the corresponding governing equations, except that variations in the horizontal directions are all neglected. The lateral boundary values for a nested grid are provided by the coarse grid values at the boundaries of the nested area.

HOTMAC outputs are used as input to a Lagrangian diffusion and transport model RaPTAD, Random Particle Transport And Diffusion. A "kernel" density estimator is used in RaPTAD where each particle represents a center of a puff. Various functional forms may be assumed to express the concentration distribution in the puff. One of the simplest ways is to assume a Gaussian distribution, where variances are determined as the time integration of the velocity variances encountered over the history of the puff. The concentration level at a given point in time and space is determined as the sum of the concentrations each puff contributes. The kernel method requires no imaginary sampling volumes, and produces a smooth concentration distribution with a much smaller number of particles than required for the previous particle method.

HOTMAC and RaPTAD were installed on fast microcomputers and tested against meteorological and tracer data collected in the summer of 1987 in Rush Valley, Utah (Williams and Yamada, 1989). Two tracer releases were simulated, one daytime and one nighttime. During the nighttime release, data gathered by a tethered instrumented balloon indicated an extremely large wind directional shear. The model was able to produce and maintain the large shear through a "nudging" term in the equations of motion which guided the winds in the upper levels toward the observed value. In order to deal with anomalous thermal winds associated with simple initial conditions, the model was initialized with very low winds. At a time appropriate to the tracer release the winds were reinitialized to the observed conditions. The modeled winds (Fig. 4) near the ground were in good agreement with the observed low level winds (Fig. 5).

The nighttime tracer concentrations displayed low dispersion and high concentrations which persisted for several hours. The plumes were rather long, and individual sites exhibited high concentrations for periods much longer than the one hour release period. The model was able to do a good job of representing this behavior which is produced by the large wind shear in the surface layer. Both the model and the observations indicated that wind fluctuations were very important in the time behavior of concentrations at various sites.

For the daytime release the dispersion was very rapid as indicated both in the observations and the model predictions. The model predicted dramatic differences between the nighttime and daytime behavior, similar to those found in the observations.

PNL/CSU Model

A version of the Colorado State University (CSU) Cloud/Mesoscale model (Tripoli and Cotton, 1982; Bader *et al.*, 1987) has been modified for use at the Pacific Northwest Laboratory (PNL) to study atmospheric boundary layer dynamics in regions of complex terrain. Although it was originally developed to simulate convective storm structure, the model's nonhydrostatic dynamical formulation coupled with a terrain-following coordinate system make it an ideal tool for the study of local and mesoscale circulations in regions of complex terrain. This model uses the dynamical equations and time-splitting numerical techniques described by Klemp and Wilhelmsen (1978) as the basis for its nonhydrostatic formulation. Additionally, the turbulence parameterization of Yamada (1983) was included to more faithfully simulate the details of nocturnal boundary layer development. The inclusion of topography is accomplished through the incorporation of the coordinate transformation described by Clark (1977).

This model's primary use has been for parametric studies of nonlinear effects of terrain geometry and surface forcing on circulations in complex terrain. Although it is not an emergency response forecast model, the results of numerical modeling experiments using this model can guide the development of new forecast tools. Recently, the model has been modified to perform large-eddy simulations (LES) of passive plume dispersion in turbulent flow. The objective of this effort is to directly simulate the small-scale concentration fluctuations of the dispersing plume (Bader and Horst, 1988). For many radionuclide and toxic chemical releases in emergency management problems, the peak instantaneous concentrations are far more important than the time-averaged concentrations. Since the experimental data on concentration fluctuations are limited, model experiments can be performed to provide a more complete data base for future parameterizations.

ARAC

Lawrence Livermore National Laboratory (LLNL) has had a continuing commitment to real time emergency response since the early 1970s, when the concept for a service to facilities requiring real time prediction of the extent of health hazards from a release of radioactivity or other toxic materials into the atmosphere was formalized as the Atmospheric Release Advisory Capability (ARAC). Prior to this, LLNL had begun development of a three dimensional diagnostic wind field model, MATHEW (Sherman, 1978), and a companion three dimensional particle in cell transport and diffusion model, ADPIC (Lange, 1973). Thus at the inception of ARAC, these codes were ready for use and were chosen as the appropriate assessment tools for ARAC's complex requirements.

The MATHEW model is used to generate a three dimensional, mass conservative gridded mean wind field across complex terrain. It uses a variational method to minimally adjust a given set of interpolated meteorological observations to account for the topographical forcing. Using mean wind fields, such as those generated by MATHEW, as input, ADPIC, a three-dimensional transport and diffusion model, predicts the time and space varying dispersal of the atmospheric pollutants. To accomplish this, ADPIC uses a particle-in-cell technique in which Lagrangian marker particles, which represent mass or radioactivity are transported inside a fixed Eulerian grid.

Although the MATHEW/ADPIC (M/A) models are still the basic ARAC models, they have been significantly improved over the 1970's versions because LLNL has continued to develop and test them using the data from major tracer field studies as they became available. Examples of these studies are represented in the field experiments of INEL (Lange, 1978), SRP (Lange, 1978), ASCOT (Lange, 1989), EPRI (Peterson and Lange, 1984), MATS (Rodriguez and Rosen, 1984), and MONTALTO (Desiato and Lange, 1985).

Throughout the 1970s and 1980s, ARAC has used the latest available M/A models in their emergency response computations. They have responded to situations such as an UF_6 spill in North Carolina, the Russian COSMOS 945 satellite re-entry, and the Three Mile Island accident (Sullivan, 1988). Recently, ADPIC, coupled with the Air Force Global Weather Central wind fields rather than with MATHEW, was used to simulate the Russian Chernobyl reactor accident (Lange *et al.*, 1988).

Recognizing the limitations of the diagnostic wind field model, LLNL has also worked on the development of predictive dynamic models in addition to improving the performance of MATHEW/ADPIC. Initial efforts have concentrated on solving the nonhydrostatic equations over domains that range from a few hundred meters to a few tens of kilometers. The models use the finite element method because of the accuracy of the method, and the ease with which irregular domains and graded grids can be handled. This work has led to a suite of closely related models that include the FEM3 model used to simulate the dispersion of heavier than air gases (Chan *et al.*, 1987) and a planetary boundary layer model used to study the atmospheric flow over complex terrain in both two (Lee and Leone, 1988) and three (Leone and Lee, 1989) dimensions.

In spite of increased computer power, the nonhydrostatic models are not yet fast enough to be used for real time emergency response. Thus, we are developing a computationally efficient hydrostatic meso β scale dynamic model that we plan to integrate into the ARAC system in the future. This model (Chan *et al.*, 1989), taking advantage of many of the techniques that we have developed in our research on the nonhydrostatic models, uses finite element techniques to solve the prognostic equations and finite difference techniques to solve the diagnostic equations. When the model is part of the ARAC system, it will augment MATHEW in supplying forecast wind fields to the ADPIC model, thus extending the time range of ARAC's predictions and enhancing its capabilities in the future.

Summary and Future Work

In the early 1970s, the Office of Health and Environmental Research (OHER) of the U.S. Department of Energy (DOE) was largely responsible for the development and implementation of three-dimensional diagnostic mass-consistent wind models that have received extensive use in the emergency response arena as both site assessment and real-time emergency response models. In the 1980s DOE/OHER has supported the development of the next generation of emergency response models through the sponsorship of the development of two- and three-dimensional prognostic models within the ASCOT program.

As part of the ASCOT program, researchers at the Atmospheric Turbulence and Diffusion Division of NOAA at Oak Ridge have enhanced an integrated puff model so that it can now be used as an inexpensive tool to simulate pollutant dispersion in valleys as well as areas of flat terrain.

Researchers at Los Alamos National Laboratory have developed the HOTMAC/RaPTAD modeling system composed of a three-dimensional hydrostatic dynamic model coupled with a Lagrangian transport and diffusion model. This modeling system, while developed on cray supercomputers, is now capable of running on desktop workstations. It is envisioned that this system will be used as an operational emergency response site system wherein the dynamic model, HOTMAC, will be continually running to forecast and save the wind and turbulence fields for the next 24 hours. Then, in the event of an accident, these fields will be readily available as input to the dispersion code, RaPTAD, to compute the surface concentration distribution of the released material.

At LLNL, there has been a continual improvement of MATHEW/ADPIC, the basic ARAC code system devoted to emergency response. In addition, they are currently developing an efficient hydrostatic model based on a combination of finite element and finite difference techniques to augment the MATHEW/ADPIC models within the ARAC system. This model will be coupled with the ADPIC dispersion model to increase the range of meteorological conditions and time scales that the ARAC system can accurately forecast.

In addition to the modeling work directly applicable to emergency response, researchers at PNL, LLNL and LANL are developing more general (and computationally more demanding) models which can deal with the nonhydrostatic pressure force, foggy or cloudy conditions, precipitation and time-varying synoptic scale conditions. Future dispersion models will also be able to compute concentration fluctuations in addition to the mean values. These efforts provide for a better understanding of the physical processes involved in complex flow and can often serve to improve model parameterizations in simpler models. Also, this work is instrumental in understanding the performance and limitations of the less rigorous, but more efficient, models used in emergency response.

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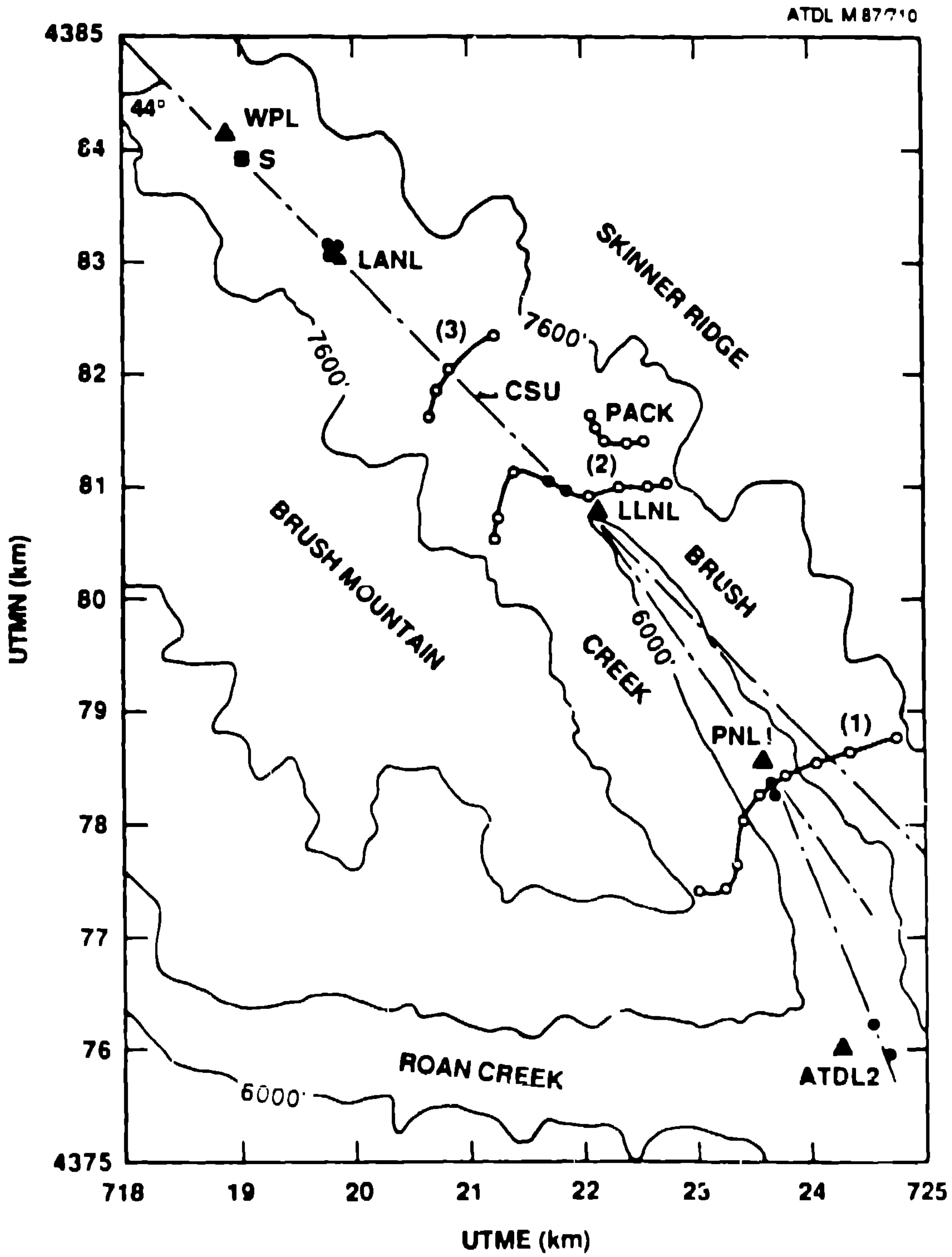
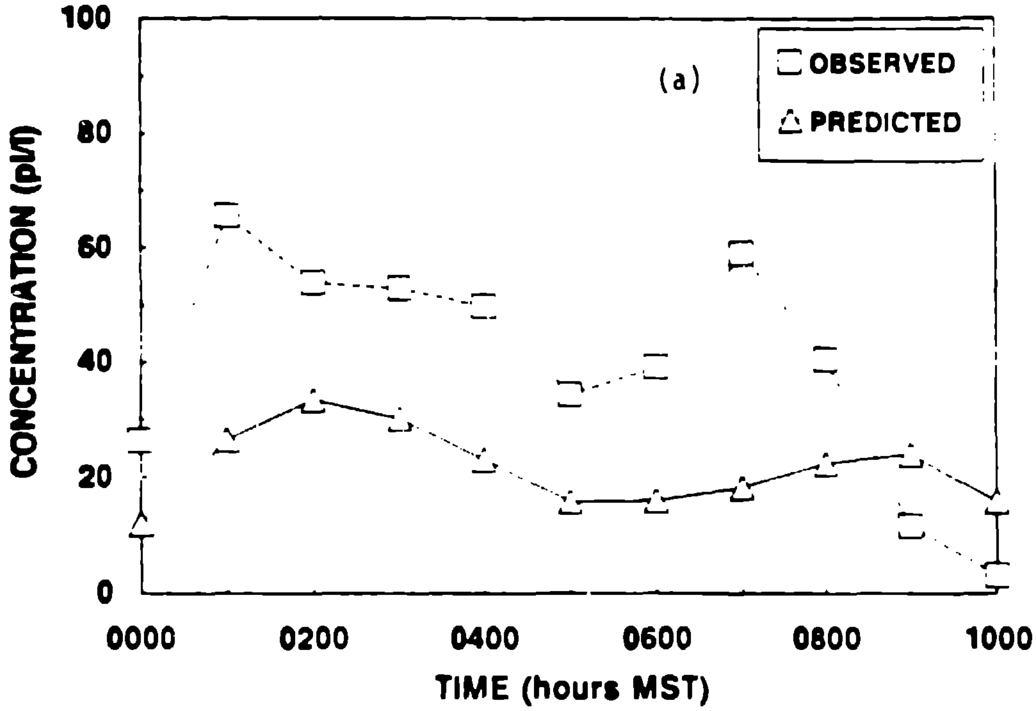


Fig. 1. Brush Creek valley showing the tracer release site (S) and sampling arcs (1), (2), and (3). Valley axis samplers are denoted by •, and arc samples by o. The tethered balloon sites are indicated by ▲. The contour heights (in feet) shown are elevations (MSL).



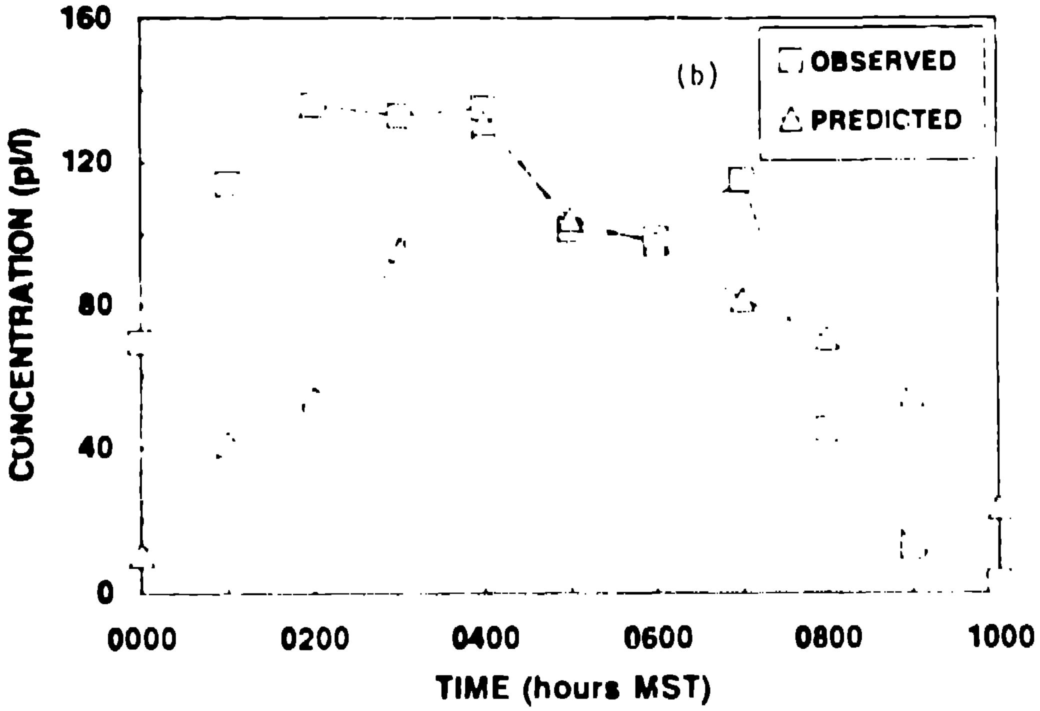


Fig. 2. Comparison of predicted and observed hourly tracer concentrations, averaged over all samplers. The times shown in the figure denote the beginning of each hourly sampling period. (a) for Test 2, and (b) for Test 4.

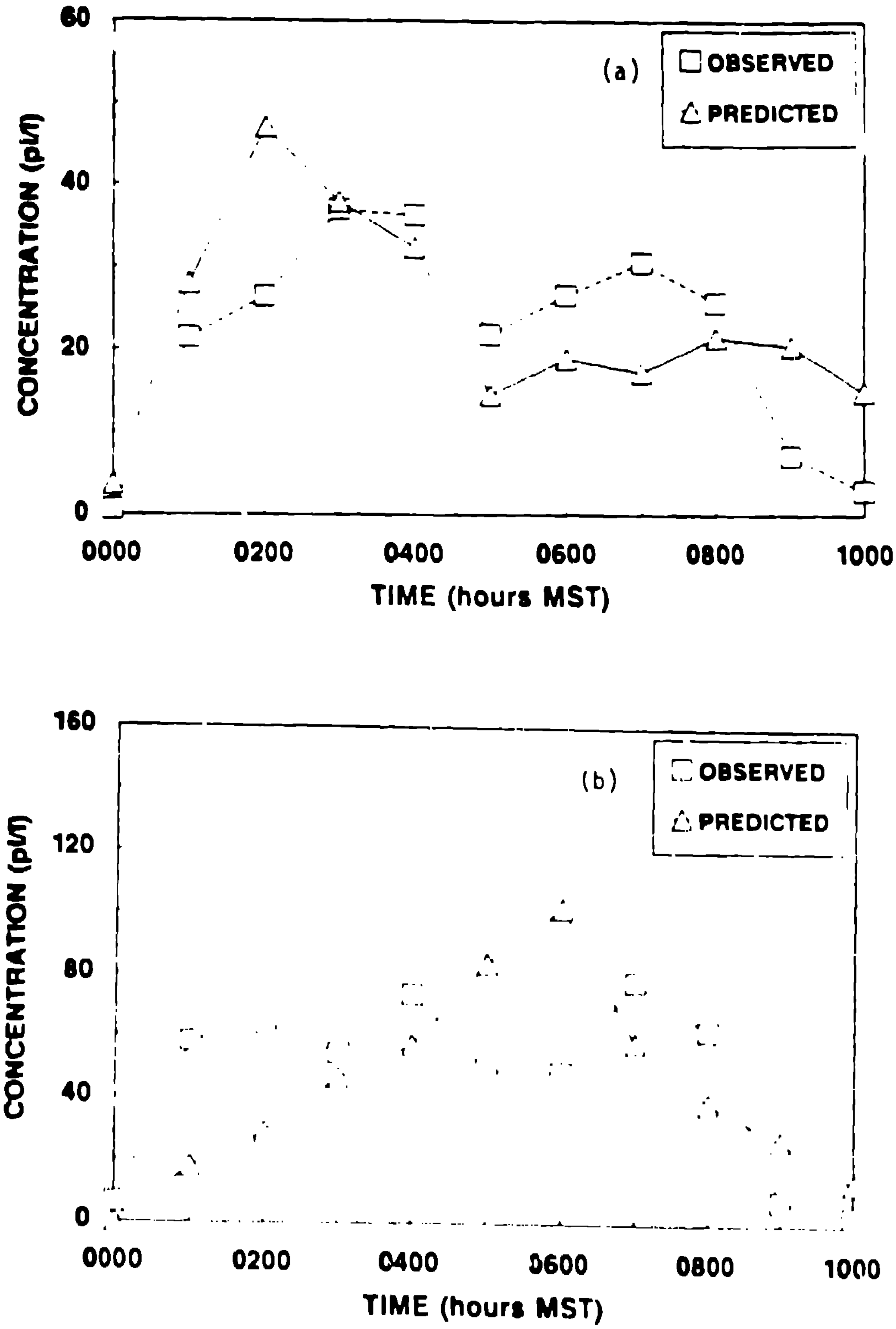


Fig. 3. Same as in Fig. 2, except for arc 1 samplers only. (a) for Test 2, and (b) for Test 4.

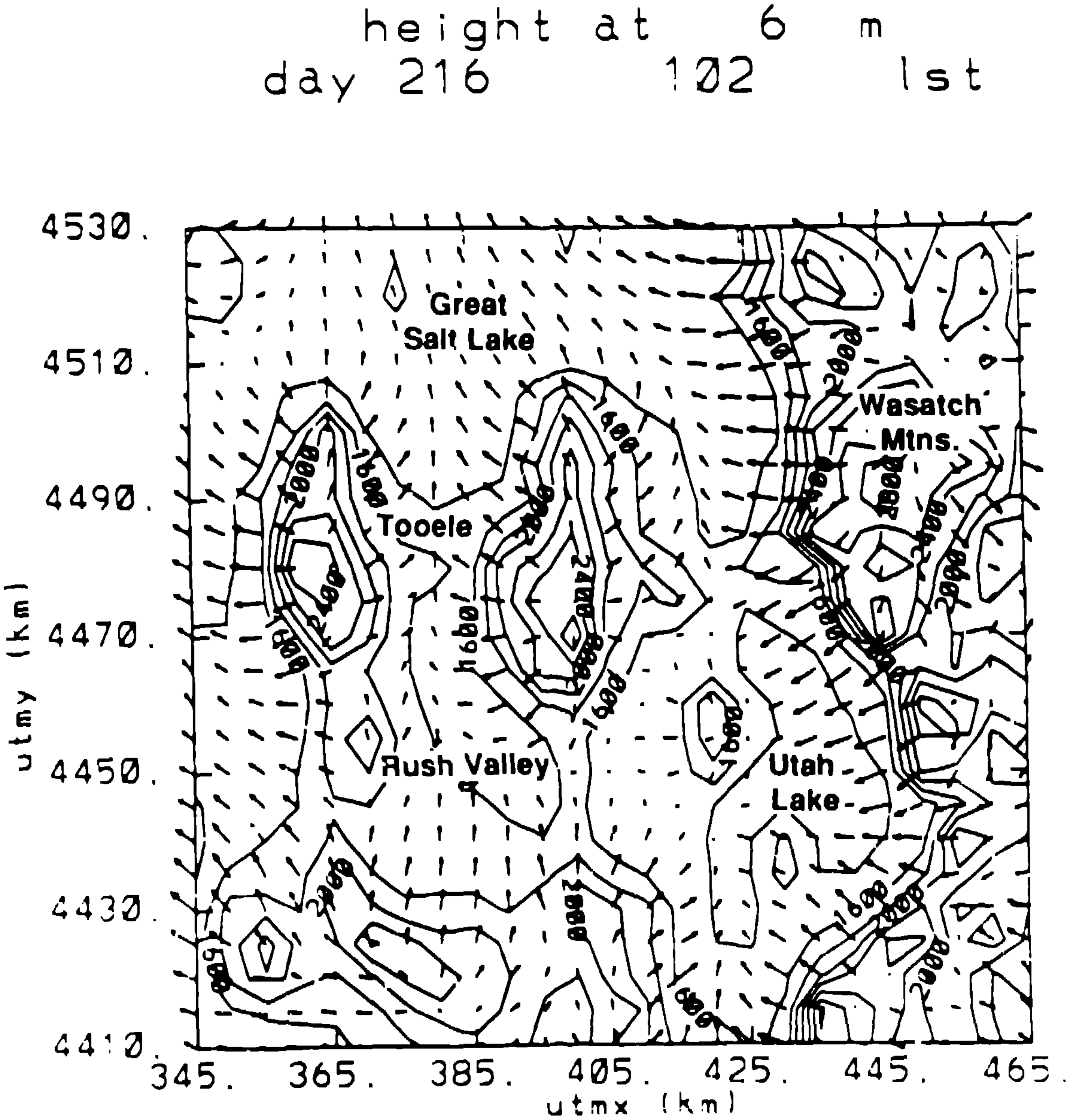


Fig. 4. Modeled 6 meter height winds for 0102 MST on August 4, 198[illegible]

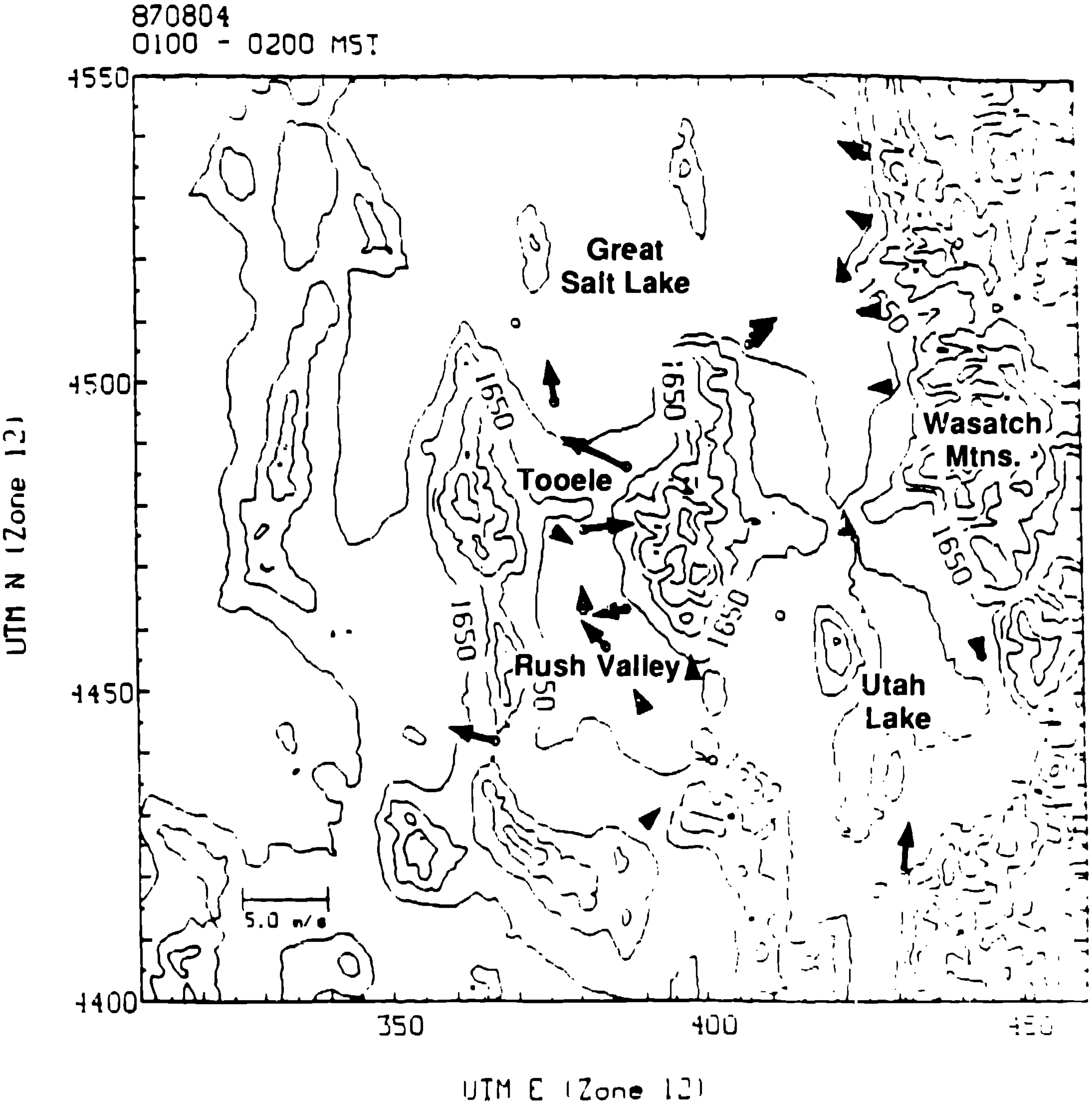


Fig. 5. Observed 10 meter average winds for 0100–0200 MST on August 4, 1987.